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$W^+W^-, W^\pm\gamma$ PRODUCTION IN PROTON COLLIDERS*

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ABSTRACT

We examine certain details of the production of electroweak pairs $WW, W\gamma$ in quark-antiquark annihilation. The polarization of the weak bosons and the effects of angular cuts are calculated. As in the $W\gamma$ angular distribution, the magnetic moment dependence of the polarizations and the WW angular distributions is striking. We note that electric moments can be studied in similar ways. Some review of other work in this area is also given.

INTRODUCTION

This is, in part, a progress report about some ongoing work[1] by our group at CWRU. We are investigating further details in the theoretical predictions for electroweak pair production, mainly W^+W^- and $W^\pm\gamma$ in proton-antiproton collisions. The issues, rates, and experimentalists are sufficiently encouraging that it now becomes important to pay attention to the actual experimental constraints.

In particular, we have now calculated the polarization of the W's and the effects of angular cuts in order to compare the decay distributions with background. Eventually, one would like to tie the polarization density matrix to the decay matrix, but it is not hard to get the final distributions from just the polarization information. The forward-backward peaking in our reactions seems well-suited for "forward spectrometry" plans in proton colliders, furnishing more reason to look at the effects of forward cuts. The hope is that small angles will be favorable for the decay leptons, enhancing the signal-to-noise ratio.

The important QCD corrections, both in the scaling violations of the proton structure functions and in unfactorized first-order corrections, have not yet been calculated by us. However, the effects of scaling violation have been considered by others and we shall reference later this work as well as other recent related papers.[2]

*Based in part on a talk presented at the Forward Collider Physics Topical Conference, Madison, Wisconsin, Dec. 10-12, 1981.

ISSUES

If and when the $W^{\pm}$ and Z^{o} are dug out of the $p\bar{p}$ debris, and even if they are found at the standard mass values

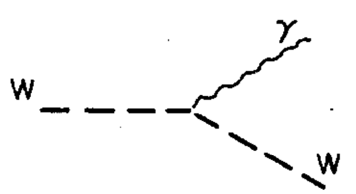
$$M_W \simeq \frac{38.5}{\sin\theta_W} \simeq 80\ \mathrm{GeV}/c^2 \qquad (1)$$

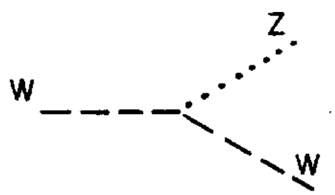
and

$$M_Z = \frac{M_W}{\cos\theta_W} \simeq 90\ \mathrm{GeV}/c^2 \quad , \qquad (2)$$

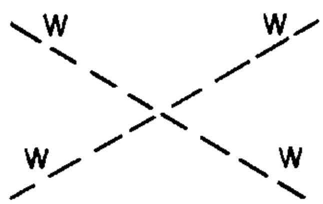
could they yet be masquerading as SU(2)xU(1) gauge bosons? Should we accept candidates with the right charge, spin and V-A couplings, and especially with the right mass?

Surely we will. It is amusing to recall the ancient circumstance where the muon passed for the pion for a number of years. A more serious challenge will yet arise in that we must find evidence for renormalizability, that is, for the gauge nature of particles. Specifically, we would like to show that self-couplings exist of <u>the form predicted</u> in the standard model or its accepted variants. These self-couplings are the trilinear $WW\gamma$, WWZ





and quadrilinear $WWWW$, $WW\gamma\gamma$, $WWZZ$, $WWZ\gamma$



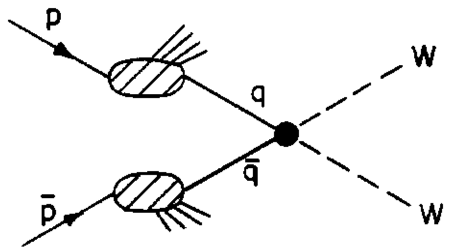
etc.

One must determine whether these exist with the predicted coupling structure and whether anomalous couplings (e.g. $ZZ\gamma$) exist. The quadrilinear couplings most probably must wait for higher energies than the regime we will address.

A few years ago, Mikaelian and I proposed looking at $p\bar{p}$ and pp collisions <u>as a test of gauge theories</u>, precisely for the WWZ and $WW\gamma$ coupling.[3] The point is that if a pair of W's is produced often enough,

$$p\bar{p}\ (pp) \to W^+W^-X \quad ,$$

presumably through quark-antiquark annihilation,



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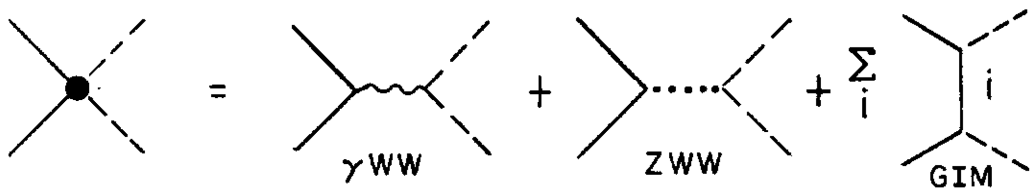
then the $q\bar{q} \to WW$ kernel depends upon the trilinear couplings



The γWW vertex involves the anomalous (an historical misnomer) magnetic moment parameter κ

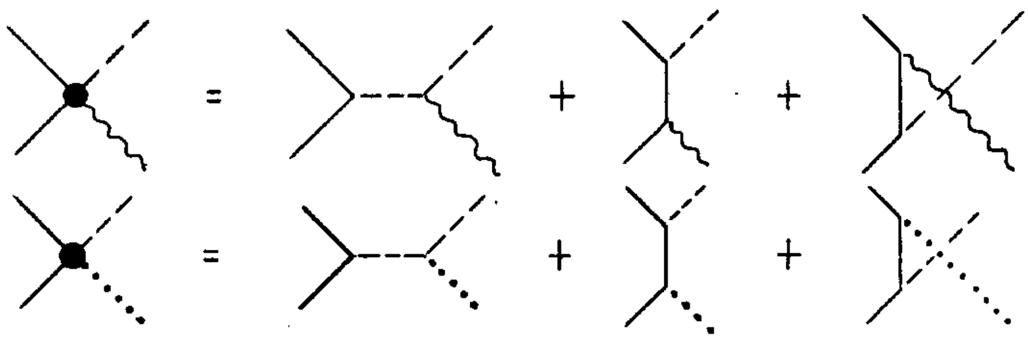
$$\mu = \frac{e}{2M_W}\,(1+\kappa) \tag{2}$$

which has the "non-anomalous" value $\kappa = +1$ in gauge theories. In contrast to γWW, the mere existence of the ZWW vertex is interesting, and it, as well as the GIM mechanism, is operative in the quark kernel.

We can also isolate γWW or ZWW by considering[4]

$$p\bar{p}(pp) \to W\gamma X \text{ or } WZX \quad ,$$

respectively. The kernels are



The procedure here and in the previous is to calculate how the rates and distributions change when the couplings are moved away from the gauge values. For example, one might consider varying κ or even omitting a vertex like ZWW altogether.

TOTAL CROSS SECTIONS

The total rates calculated in a scaling limit (no QCD corrections) are shown in Fig. 1 for $p\bar{p}$. In order to define the $W\gamma$ reaction, a lower limit of 5 GeV for the photon laboratory energy is used. The relative sizes for the various electroweak pair production cross sections can be readily understood. With such a cut on the photon energy the $W\gamma$ reaction is close to resonance (single W production). Since the neutral current couplings are suppressed for $\sin^2\theta_W \cong \frac{1}{4}$, the WZ and ZZ rates are an order of magnitude below that for WW.

At the SPS c.m. energy of $\sqrt{s}$ = 540 GeV and luminosity $L = 10^{30}$ cm^{-2}s^{-1}, several $W\gamma$ events per day are predicted. We have to go to the Tevatron region of $\sqrt{s} \geq 1000$ GeV for a WW daily event. (It must be emphasized that QCD corrections are a big question mark. We return to this later.) Improvement in luminosity will be needed for the other channels and in this regard ISABELLE offers more hope - the pp cross sections are not that much smaller.

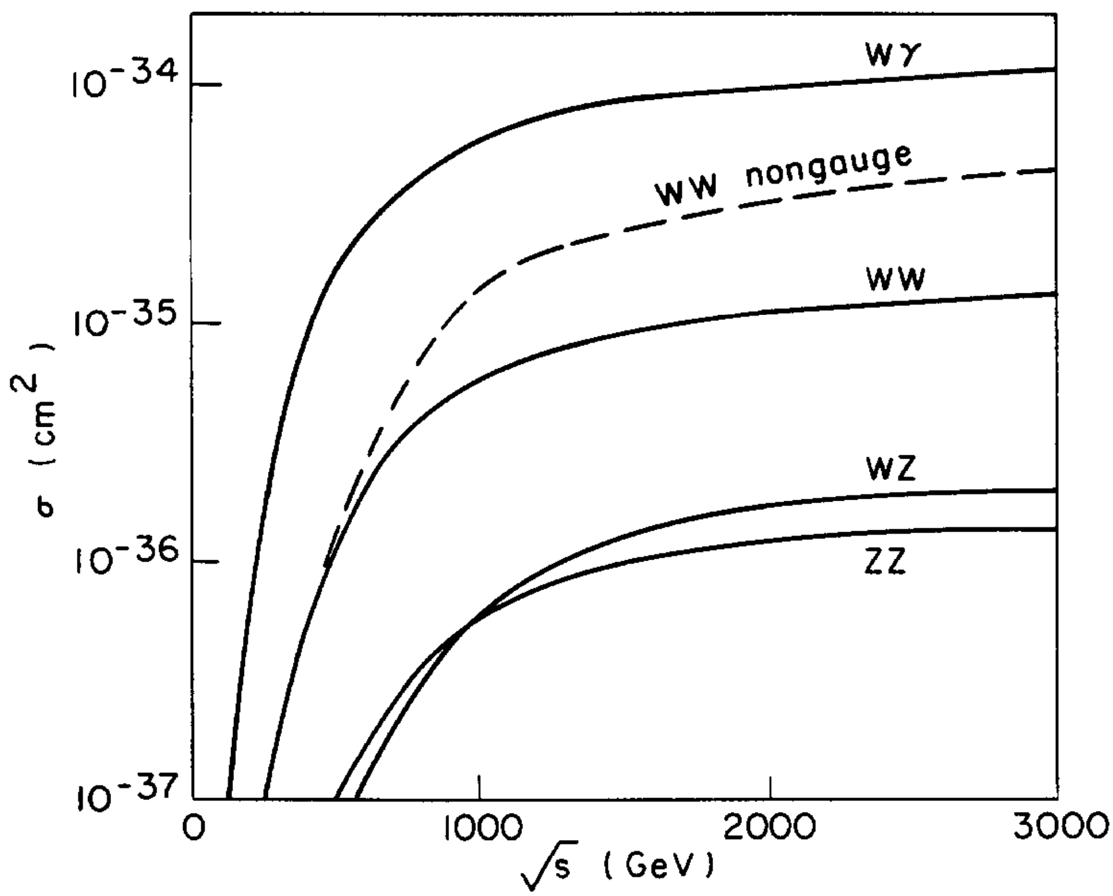


Fig.1. Total cross sections for the production of boson pairs, $p\bar{p} \to$ pair + X . No QCD corrections.

HIGH ENERGY BEHAVIOR

What tells us that the pairs have the appropriate gauge couplings? First, the self couplings keep the high energy behavior[3,4] of the basic fermion-antifermion $\rightarrow$ WW cross section under control, the hallmark of renormalizability. (Historically, the $f\bar{f} \rightarrow$ WW reaction has been a focal point in the study of high energy limits.) This is seen in Fig. 2 and translates into the result for $p\bar{p} \rightarrow$ WWX shown in Fig. 3. A comparison with a result where there is no ZWW coupling is also shown in Fig. 2 and Fig. 3 (where phase space eventually cuts off the nongauge result as well). The dashed curve in Fig. 1 represents the corresponding nongauge total rate.

Perhaps it is possible to make sense out of a calculation where, for example, the WWZ interaction can be neglected. We have in mind some sort of composite model for the W where pair production cross sections could get large. Then the differences discussed above are meaningful and the general gauge mechanisms which keep multi-W production at the electromagnetic level could be probed in this way.

Such important cancellations also take place in WZ and Wγ production and, conversely, are ruined for nongauge choices for the couplings. ZZ production is both rarer and less interesting. It is QED-like and only anomalous γZZ couplings would make its story similar.

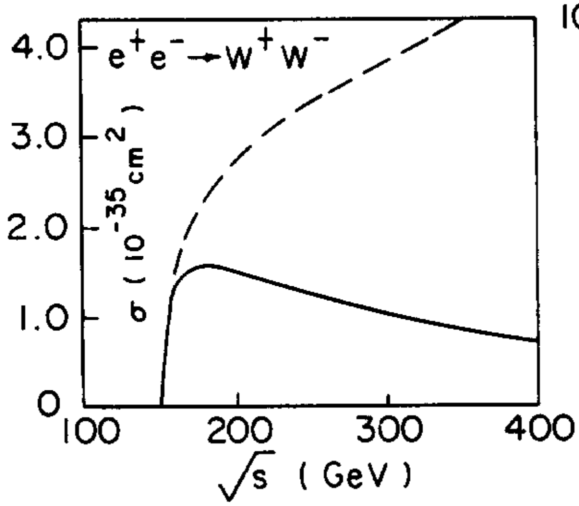


Fig.2. Total cross section for $f\bar{f} \rightarrow$ WW where $f = e^-$, for example. The dashed curve is a nongauge result.

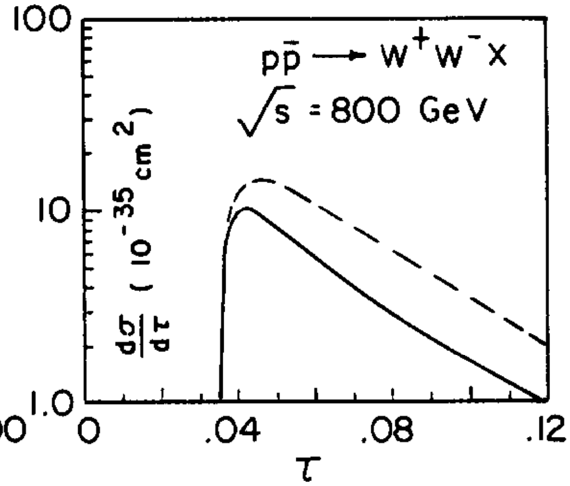


Fig.3. Invariant-mass distribution with $\tau = Q^2/s$. The dashed curve is a nongauge result.

ANGULAR DISTRIBUTIONS - OLD RESULTS

After the gauge cancellations, the fermion-exchange diagrams dominate the angular distributions. Indeed, the forward peaking for WW and forward-backward peaking for WZ,ZZ, and Wγ are seen in the figures of Refs. 3. and 4. If non-Abelian gauge invariance is not respected, we expect the WW,WZ, and Wγ angular distributions to be "filled in" as the s - channel poles become more important.

This is spectacularly verified in Fig. 4 where the results for the $u\bar{d} \to W^+\gamma$ have been reproduced from Ref. 4. We see a new feature, a "gauge zero" in the angular distribution where the cross section vanishes [See Eq. (2.19) of Ref. 4.] at $\kappa = 1$. The resultant angular distributions for the proton collisions are shown in Ref. 5 and a pronounced dip survives in the Wγ c.m. frame. For massless fermions, the $q_i\bar{q}_j \to W^+\gamma$ has a zero at the c.m. angle between γ and $\bar{q}_j$,

$$\cos\theta = 1 + 2Q_j \quad , \quad \kappa = 1 \tag{3}$$

independent of all other factors. Thus only the sea-sea annihilation contribution to $p\bar{p}$ collisions fills in the zero, and negligibly at that.

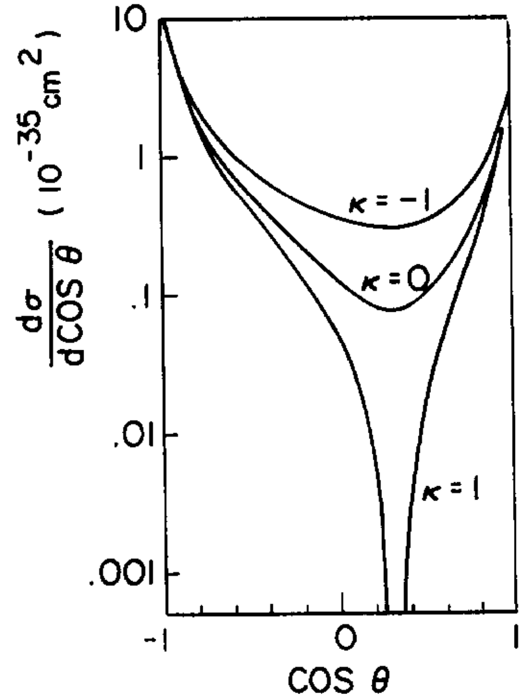


Fig. 4. Angular distribution for $u\bar{d} \to W^+\gamma$ at $\sqrt{s}$ = 150 GeV. θ is the c.m. angle between u and W^+.

It has been shown[6] that the zero corresponds to factorization of the four-body tree amplitude, the necessary ingredients being one massless boson and a gauge trilinear coupling. The factored form consists of an "Abelian" amplitude times a group-theoretical factor, the latter possibly vanishing for certain angles and reactions. This is the second of two theorems in which we are interested[7]. Although there are related zeros in gluon amplitudes, the massless particle should couple to an observable quantum number for an experimental test.[8] The upshot of a survey through various possibilities is that $q\bar{q} \to W\gamma$ seems to offer a unique opportunity to see such a zero. Note there is a related zero[9] in the Dalitz plot for $W \to q\bar{q}\gamma$ and a quasi-zero[4] in $q\bar{q} \to WZ$, but these are harder to measure.

The problem we face in the measurement of the $W\gamma$ dip is not just whether background or radiative corrections will obscure the dip, a point to which we will return later, but also the fact that the events are essentially forward/backward even for $\kappa \neq 1$. We expect that it may be hard to find non-forward events in a first generation experiment.

ANGULAR DISTRIBUTIONS - NEW RESULTS

We have now calculated[1] the κ dependence of the WW angular distribution and the results for $\kappa = \pm 1, 0$ and for the quark reaction $u\bar{u} \to WW$ are seen in Fig. 5. (The dependence on κ is quadratic so that three values tell all.) This linear plot shows that significant numbers of non-forward events can be found if κ is varied away from unity. In contrast to a need to distinguish dips of varying size, sizeable humps can appear in the nongauge cases. The disadvantages here in comparison to $W\gamma$ lie in the smaller rate and the presence of both trilinear couplings.

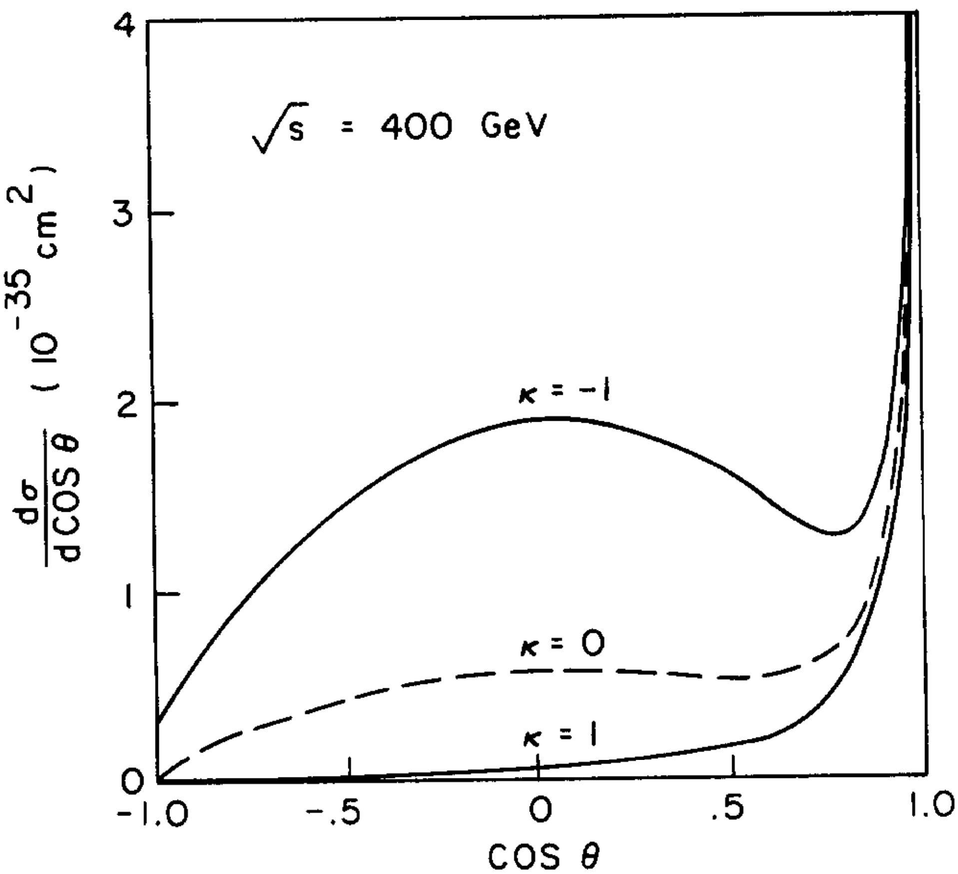


Fig.5. Angular distributions for $u\bar{u} \to WW$ as a function of the magnetic moment. θ is the c.m. angle between u and W^+. $d\bar{d} \to WW$ is reflected in $\cos\theta$ and reduced in size.

In any case, there are sufficient forward-backward events to qualify as a forward-collider prospect. For $\kappa = 1$, we have inserted angular cuts in the parent $p\bar{p} \to WWX$ reaction. (For $\kappa \neq 1$, we only gain cross section.) As $\sqrt{s}$ grows from 600 GeV to 2000 GeV, we estimate that the percentage of the events where both W's are inside 20^{o} grows from 7% to 30% and the percentage of the events where either is inside 20^{o} grows from 50% to 60%. One of the W's may wander at larger angles depending on the decay muon detection capability.

POLARIZATION

We have also calculated the polarization density matrix for the W spin in the quark reactions. Ultimately the distributions in angle for the decay leptons is needed, and the density matrix will tell us something about those distributions.

In the $u\bar{d} \to W^{+}\gamma$ c.m. frame, the angular-averaged and normalized density matrix yields the polarization which is given in Table I as a function of energy and κ. It is seen that the polarization is highly κ dependent, and that the longitudinal helicity state dominates at high energy in the non-renormalizable $\kappa \neq 1$ theories as expected. At $\kappa = 1$, we achieve 80% right-handed (RH) polarization for the W^{+} at high energies.[10] This is due to the dominant backward peak, of Fig. 4 where the W^{+} lies close to the $\bar{d}$. The forward peak corresponds to a LH W^{+} and angles near the zero give intermediate results. The $d\bar{u} \to W^{-}\gamma$ has the handedness reversed. A useful picture here is that a weak boson tends to follow the handedness of any collinear fermion from which it has been emitted.[11] The implications for a decay muon will be discussed in the next section.

Table I W^{+} polarization in $u\bar{d} \to W^{+}\gamma$

$\sqrt{s}$ (GeV)	κ	LH	Long.	RH
	1	19%	3%	78%
100	0	19%	4%	77%
	-1	19%	5%	76%
	1	20%	0%	80%
400	0	16%	21%	63%
	-1	11%	50%	39%
	1	20%	0%	80%
800	0	10%	51%	39%
	-1	4%	80%	16%

The corresponding averaged polarizations for $u\bar{u} \to WW$ are listed in Table II. At high energy, one again sees the longitudinal dominance for $\kappa \neq 1$. For $\kappa = 1$, the W^+ is LH for $u\bar{u}$ and our calculations show RH for $d\bar{d}$. (The reverse is true for W^-.) This is also consistent with W following the handedness of its parent quark at small angles. Note that all of the polarization states contribute at low energies where the $\kappa = 1$ cross section is largest. The significance of this is discussed next.

Table II W^+ polarization in $u\bar{u} \to WW$

$\sqrt{s}$ (GeV)	κ	LH	Long.	RH
	1	50%	29%	21%
170	0	50%	30%	20%
	-1	47%	32%	21%
	1	65%	21%	14%
200	0	60%	26%	24%
	-1	52%	36%	12%
	1	96%	1%	3%
800	0	8%	91%	1%
	-1	3%	96%	1%

DECAY DISTRIBUTIONS

In the rest frame decay $W^+ \to \mu^+\nu_\mu$, the μ^+ likes to follow the spin of the W^+ and the specific distribution is $(1 + s\cos\theta^*)^2$ for RH ($s = +1$) or LH ($s = -1$). It is $\sin^2\theta^*$ for longitudinal polarization. θ^* is the μ^+ angle along the spin axis of quantization. A Lorentz boost of the LH case along this axis leaves a hole in the forward direction:

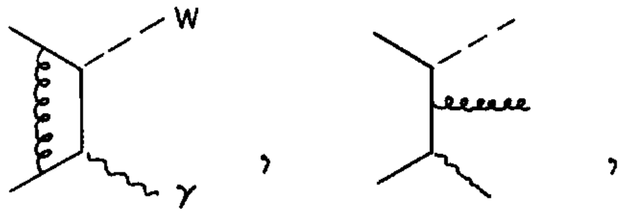
We therefore can say that the W produced in $p\bar{p} \to W\gamma X$ has the same sort of boost picture for decay as in single W production if $\kappa = +1$. However, it remains to be seen whether this will hold for $\kappa \neq 1$. The significance is that the background (single W's, etc.) may be reduced for $\kappa \neq 1$ events.

Even more interesting is the fact that the W pairs produced in $p\bar{p} \to WWX$ are dominated by low invariant mass so that there is sufficient mixture of all polarizations even for

$\kappa = 1$. Therefore our calculations give hope that the background may be suppressed where pairs of W's are to be found.

QCD AND OTHER CORRECTIONS

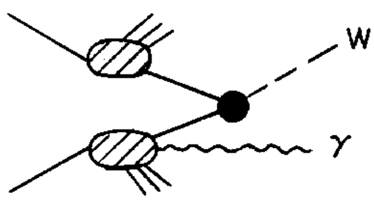
It is straightforward to include the (logarithmic) scaling violations in the quark distributions and this is discussed in a separate conference contribution.[12] It appears that QCD-corrected structure functions can lead to order-of-magnitude reductions in the cross sections near threshold but also can turn around and increase the rates at higher energies. For a better assessment we should calculate the "constant" terms in first order QCD:



etc.

Such terms are important in single W production and their calculation is in progress.[1]

Another question is the size of non-leading terms such as



etc.

For smaller cuts on the photon energy, such contributions must be considered.

ELECTRIC QUADRUPOLE AND DIPOLE MOMENTS

In addition to the magnetic dipole moment freedom, there is also an arbitrariness in the electric quadrupole for a spin-one particle. Equivalently, there are two arbitrary parameters[13] κ and λ in the magnetic dipole moment.

$$\mu = \frac{e}{2M_W} (1 + \kappa + \lambda) \tag{4}$$

and the electric quadrupole moment

$$Q = - \frac{e}{M_W^2} (\kappa - \lambda) \ . \tag{5}$$

The higher derivative electromagnetic interaction associated with $\lambda \neq 0$ gives rise to high energy behavior more vicious than $\kappa \neq 1$. This a priori possible freedom should be included in any test scenario and may be the first parameter constrained by any experimental results.

The electric dipole moment is zero if the W's electromagnetic interaction is time-reversal and parity invariant. However, this could and should be tested by computing how distributions are changed by its inclusion.

FUTURE WORK AND PROGNOSIS

We have reported some preliminary results in a project to assess the possibility that gauge self-couplings could be tested with proton colliders. This developing area of research is now at a stage where detailed experimental questions must be answered, and plans are for a Monte Carlo simulation of the $W\gamma$. The polarization density matrix is to be tied to the decay matrix in order to compute distributions in photon and muon angles. Also, we are investigating QCD radiative corrections and non-leading (higher twist) contributions, especially as they affect the $W\gamma$ zero. The related assessment of WW involves very similar steps.

We now see three ways to get a handle on κ. (1) Any bound on the overall rate will give a bound on κ. (2) The shapes of c.m. angular distributions (dips and humps) are very sensitive to κ. (3) The polarization for $\kappa \neq 1$ is markedly different from $\kappa = 1$. It appears that λ can be probed in related manner. The form of the ZWW vertex could also be generalized in terms of parameters like λ and κ, with qualitatively similar results.

ACKNOWLEDGMENT

We are grateful to David Cline for important suggestions and for his interest in this work.

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